Lawrence Livermore National Laboratory

From QCD to Nuclei to Stars

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Low-Energy nuclear physics

- Overarching goal:

To arrive at a comprehensive and unified microscopic description of all nuclei and their low-energy reactions from the basic interactions between the constituent protons and neutrons

- This is a lofty and ambitious goal that has been a "Holy Grail" in physics for over fifty years
  - Nuclei are self-bound, two-component quantum many-fermion system
  - Complicated interaction with at least two- and three-nucleon components
  - We seek to describe the properties of "nuclei" ranging from the deuteron to super-heavy nuclei and neutron stars

Our goal is to arrive at an *ab initio* picture for light nuclei and their reactions

Where do we start?

- Quantum chromodynamics (QCD) is the underlying theory for the strong interaction
  - Lattice QCD calculations are far too difficult to do complex nuclei
    - At best they might be able to treat two nucleons
    - They are not capable of providing an accurate nucleon-nucleon interaction in foreseeable future
      - But they can verify that QCD is the correct theory for the strong interaction between hadrons
- We need a theory with point-like nucleons and an interaction based on QCD
  - Effective field theory (EFT) based on the properties of QCD provides an elegant solution with broad predictive power

Effective Field Theory

- Based on the symmetries of QCD
  - Degrees of freedom: nucleons + pions
  - Describes pion-pion, pion-nucleon and inter-nucleon interactions at low energies
- Systematic low-momentum expansion to a given order

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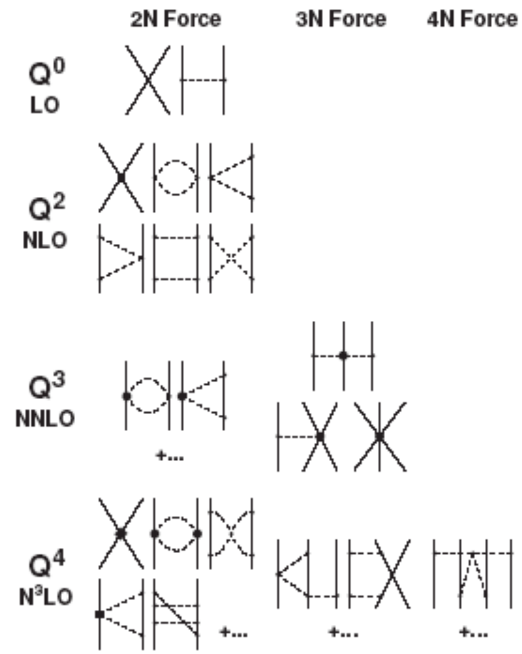

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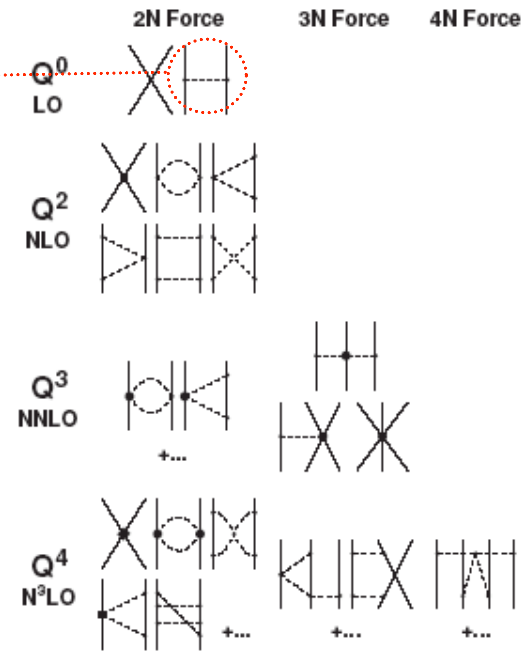

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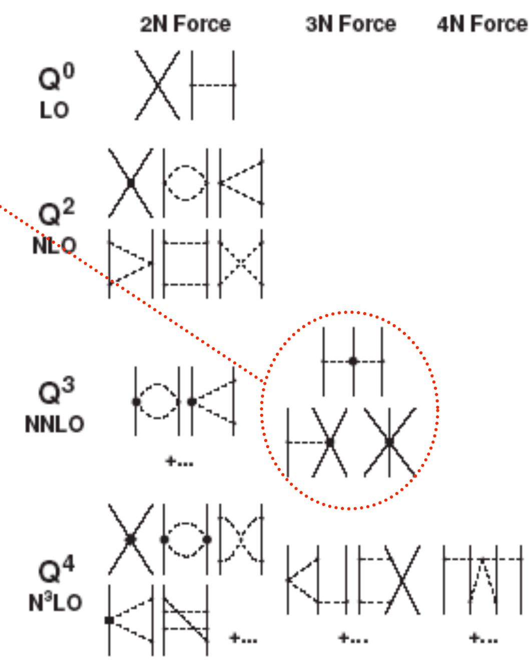

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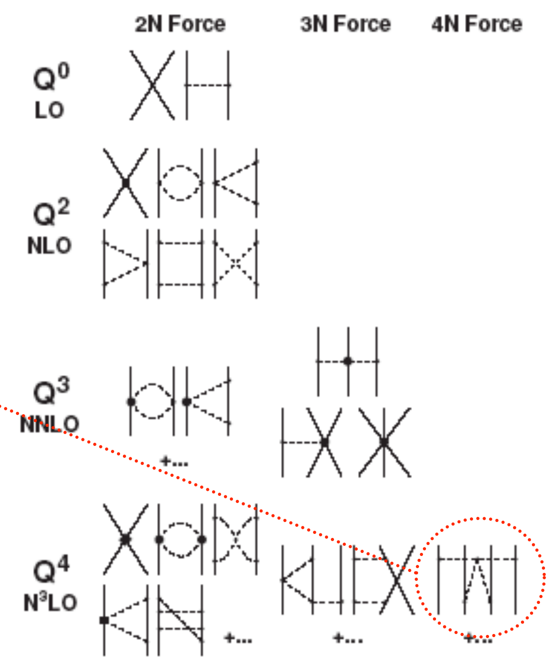

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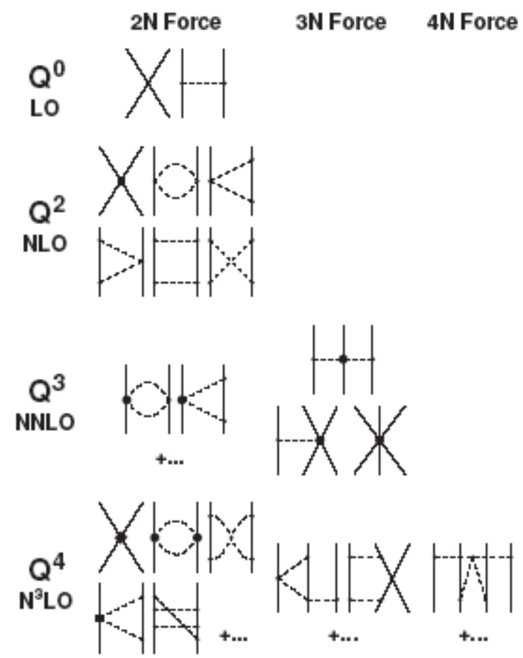

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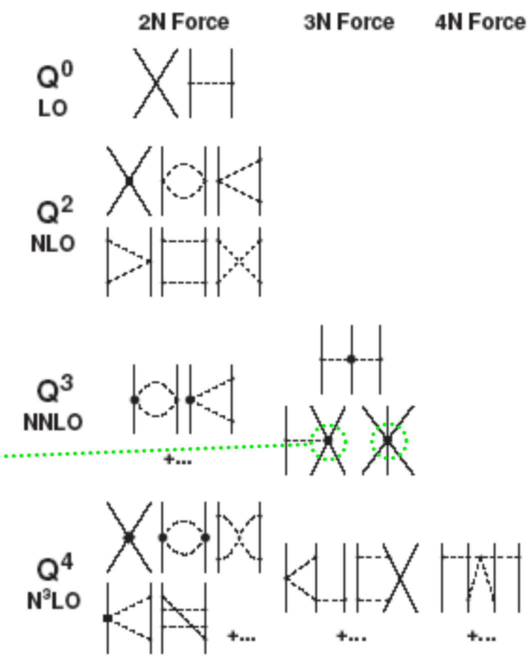
  - NN parameters enter in the NNN terms etc.
- Low-energy constants (LECs)
  - Low-energy theory, integrates out short-range physics
  - Only <u>two</u> NNN and <u>none</u> NNNN low-energy constants up to N^3LO



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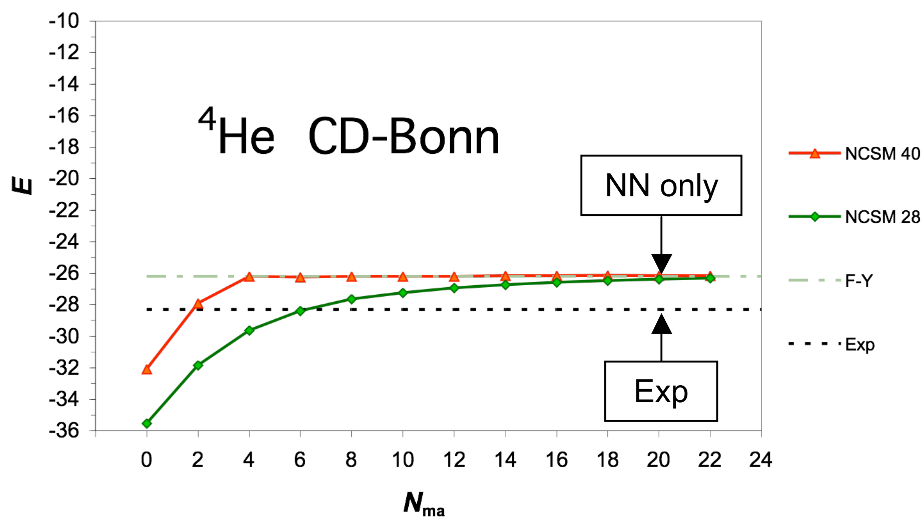

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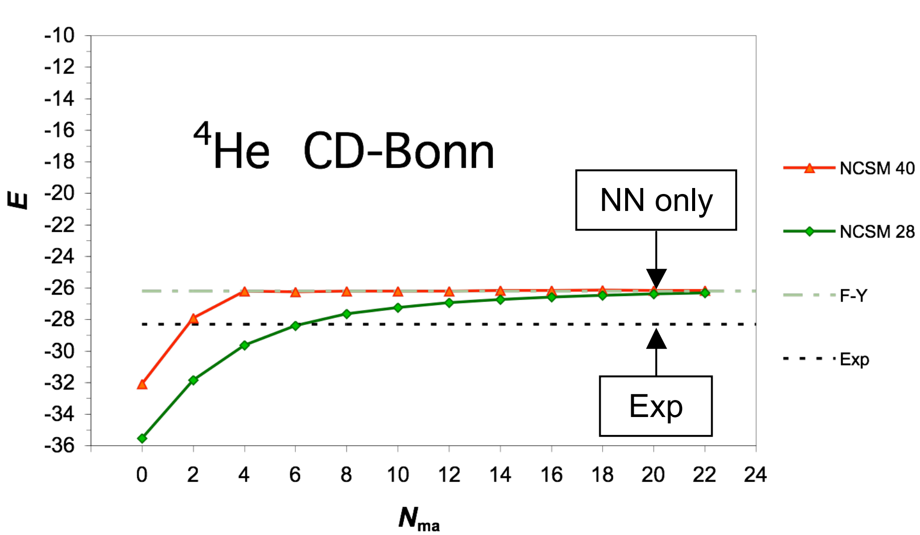

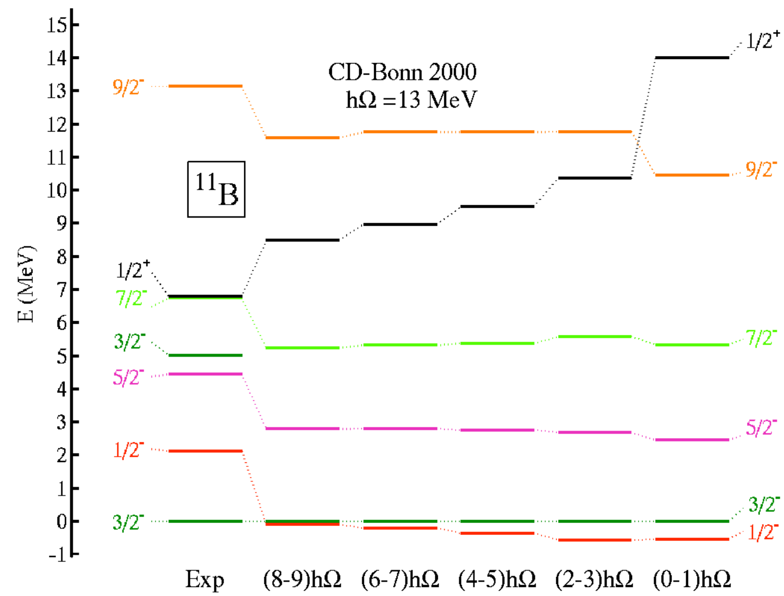

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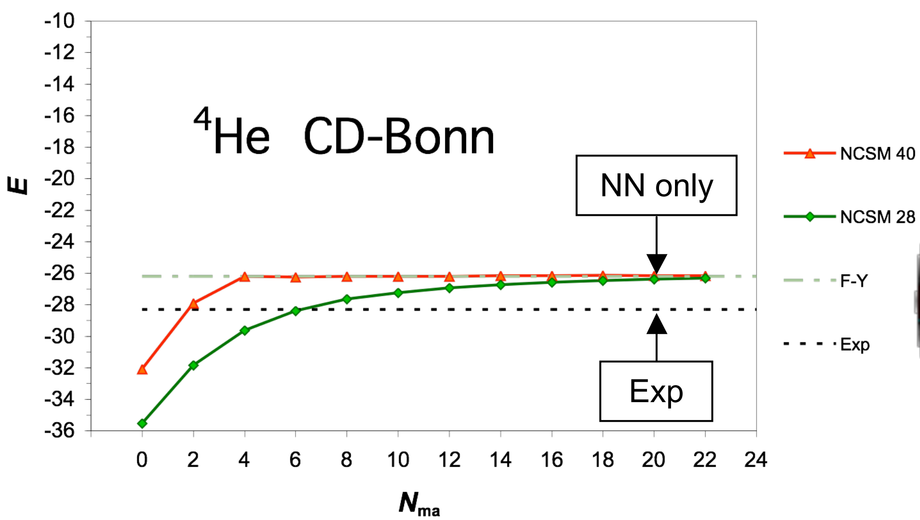

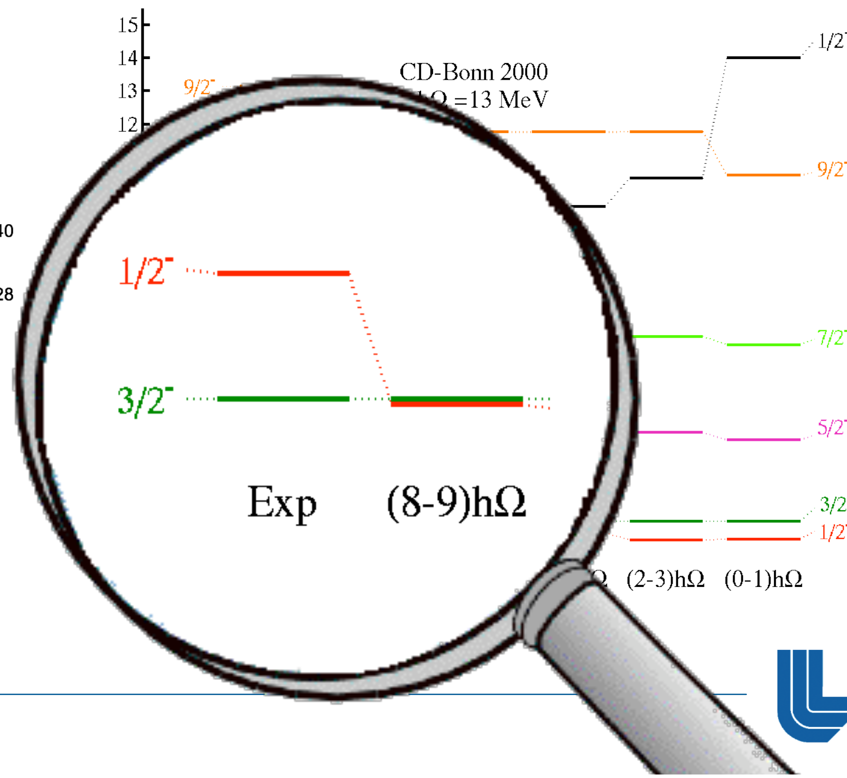

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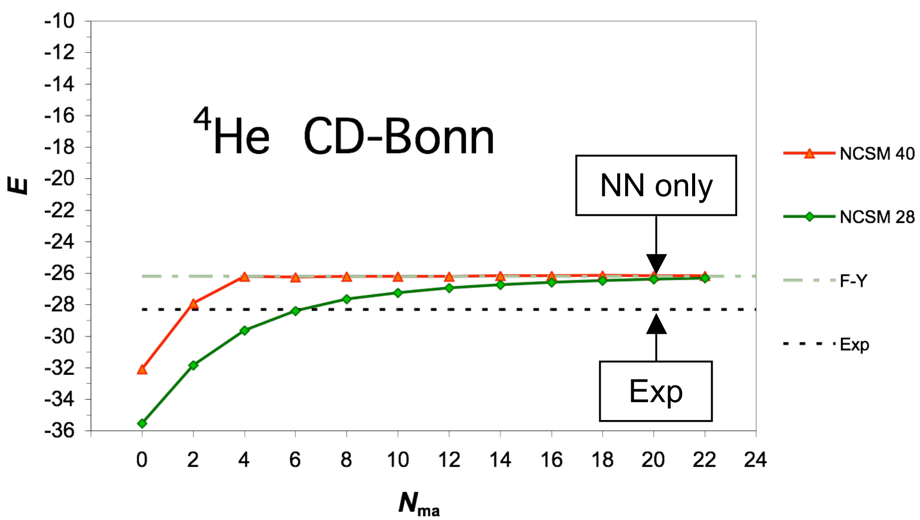
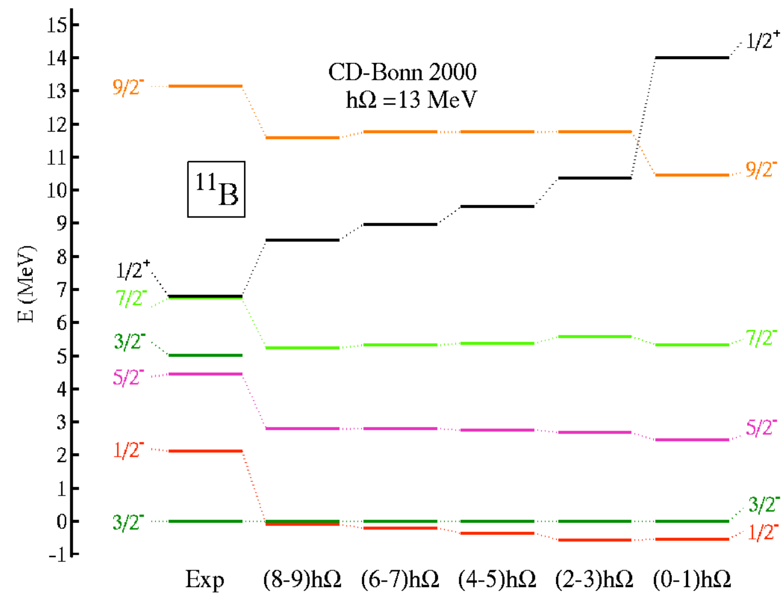
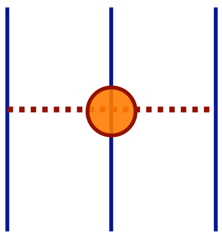
- Predicted by QCD symmetries





The NNN interaction

N^2LO

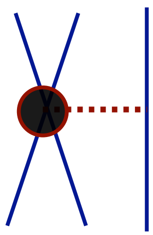


$c_1,\ c_3,\ c_4$

Two-pion exchange

c_1,c_3,c_4 LECs appear in the chiral NN interaction

- Determined in the A=2 system



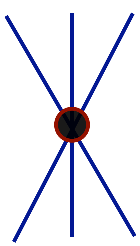
c_D

New!

One-pion-exchange-contact

New c_D LEC

Must be determined in $A \geq 3$ system



c_E

New!

Contact

New c_E LEC

Nontrivial to include in many-body calculations

– Large-scale computational problem: **ATLAS**

Computational many-body method for nuclei

$$H|\Psi\rangle = E|\Psi\rangle$$

- *Ab initio* No-Core Shell Model
- Many-body Schrödinger equation
  - *A*-nucleon wave function
- Realistic nuclear Hamiltonians (NN+NNN)
- Harmonic-oscillator basis
  - Basis size determined by allowed oscillator excitations N_{max}
  - Construct effective interaction appropriate to the basis
- By construction **convergent to exact solution** with basis enlargement and/or increase in cluster size in the effective interaction

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Six-Nucleon Spectroscopy from a Realistic Nonlocal Hamiltonian

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***Ab Initio* Shell Model Calculations with Three-Body Effective Interactions for *p*-Shell Nuclei**

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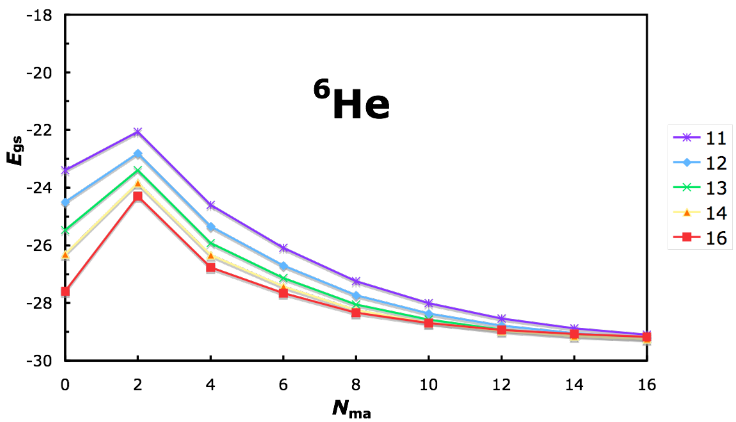
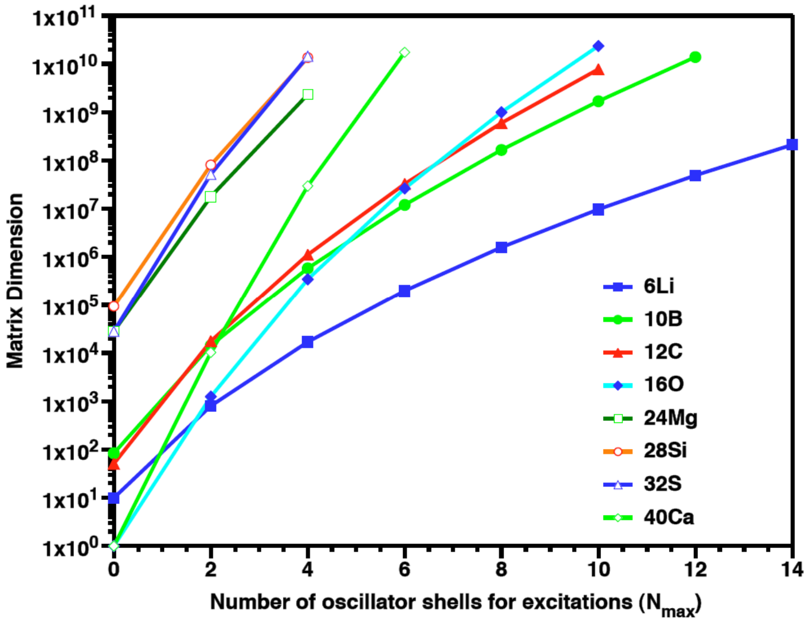
(Received 19 November 2001; published 2 April 2002)

Computationally demanding problem

- Convergence governed by N_{max}
- Basis dimension grows with N_{max}

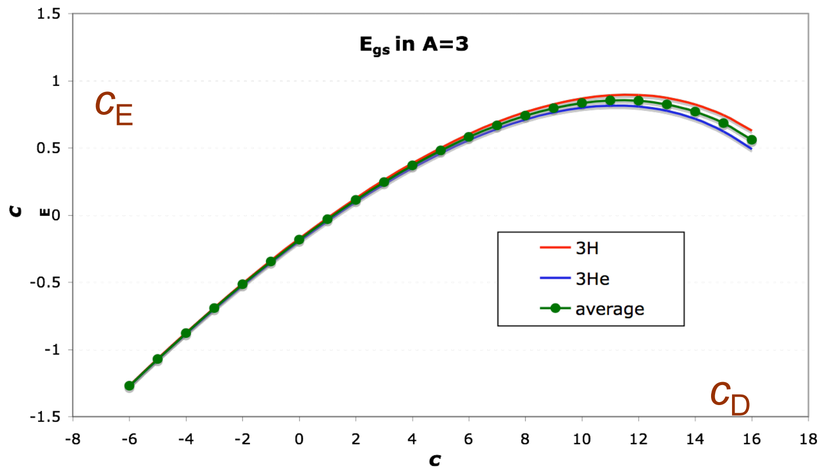




- Typical calculation for ^{12}C with N_{max}=6
- Matrix dimension N_D=32M
- Number of NNN matrix elements ~ 700M
- Memory for matrix 8 TB
- N_{proc}=3828
- CPU=11,500 h
- Scales as $N_D^{3/2}$

Determining the three-nucleon interaction: *A*=3 & ^{4}He

- Constrain c_D, c_E to A=3 binding energy



c_D - c_E dependence that fits *A*=3 binding energy

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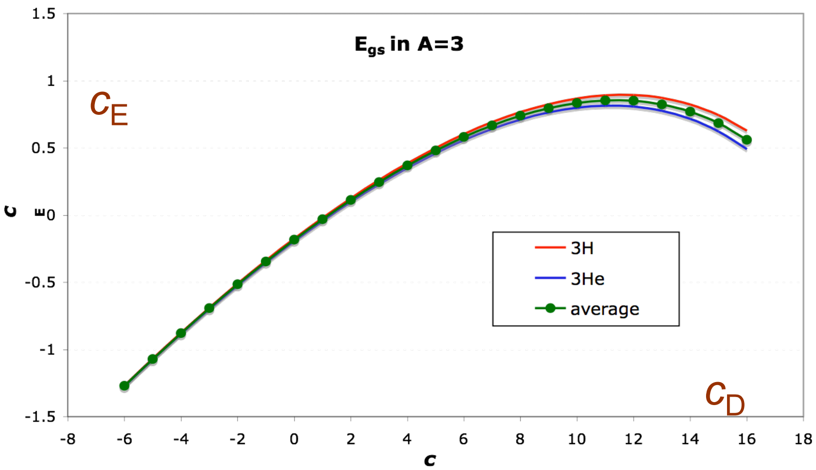
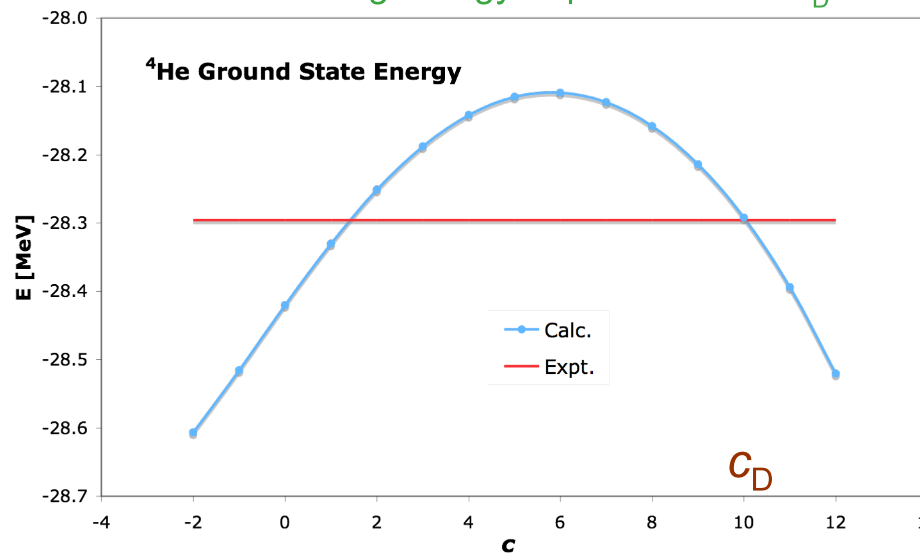


- Other observables are needed:
  - N-d doublet scattering length
    - Correlated with E_{gs}
- ^{4}He binding energy
- Two combinations of c_D - c_E that fit both A=3 and ^{4}He binding energies
  - ^{4}He E_{gs} dependence on c_D weak
    - ^{4}He and A=3 binding energies correlated

^{4}He binding energy dependence on c_D



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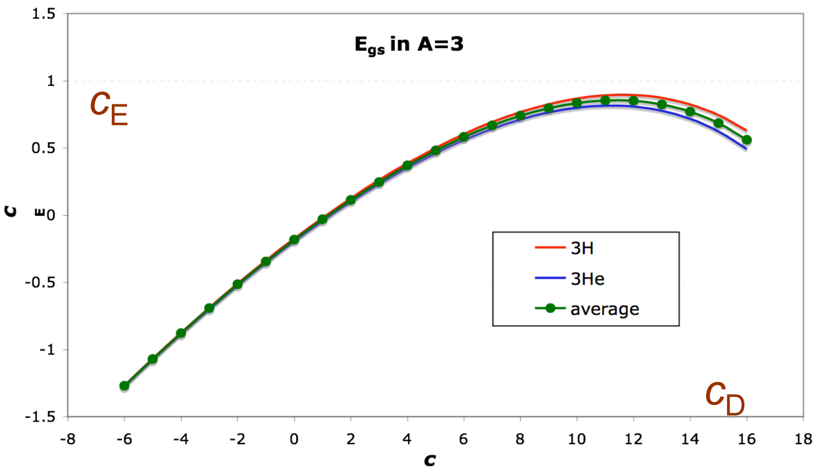

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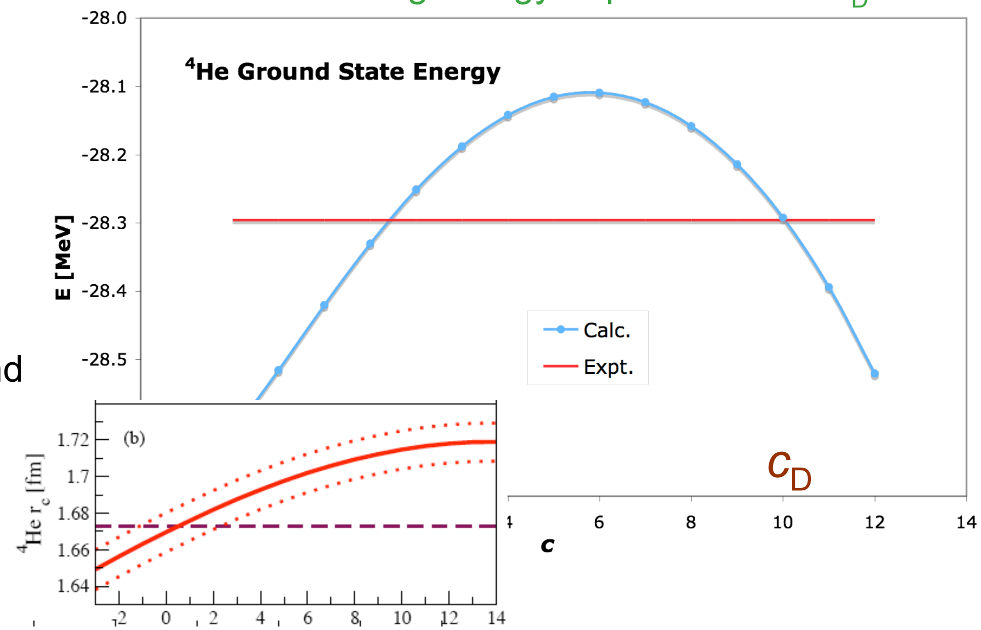

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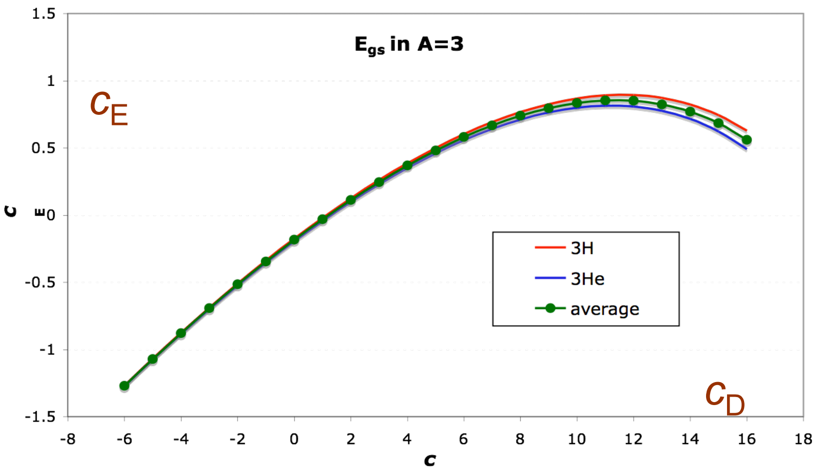

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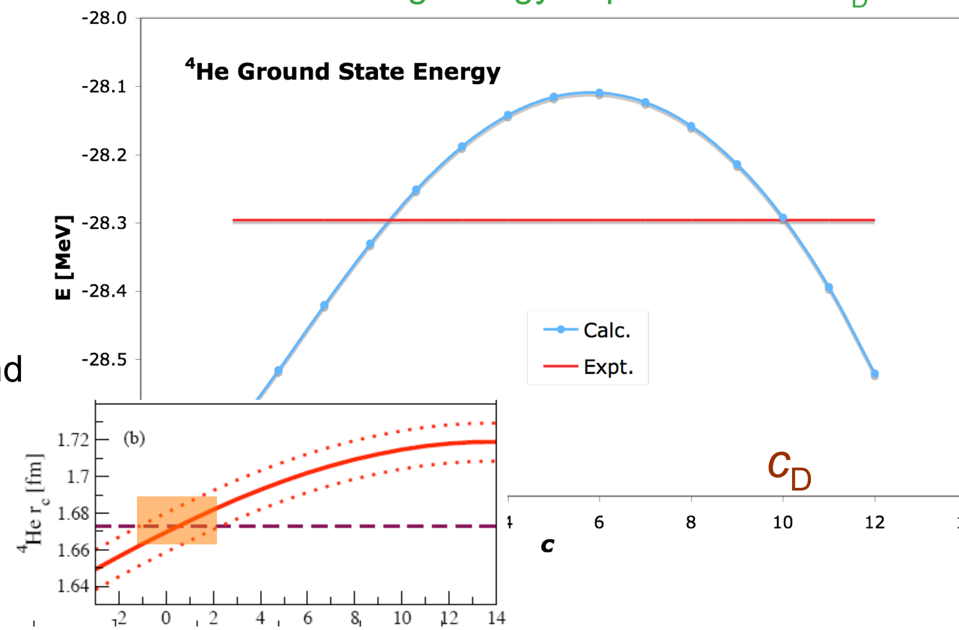

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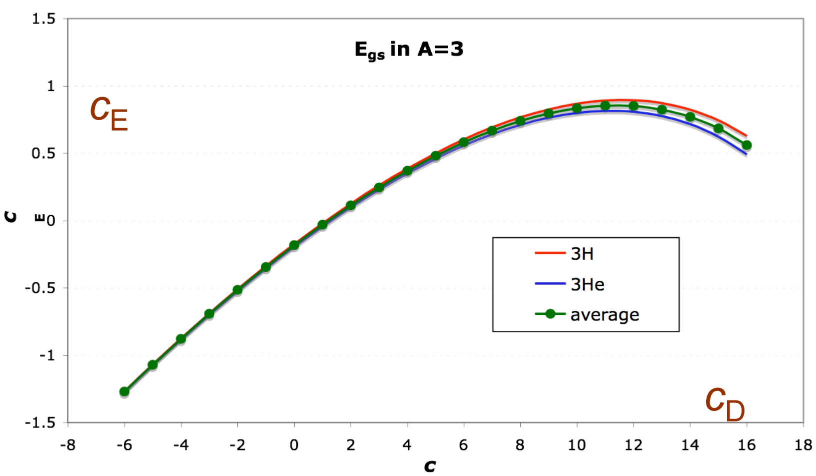

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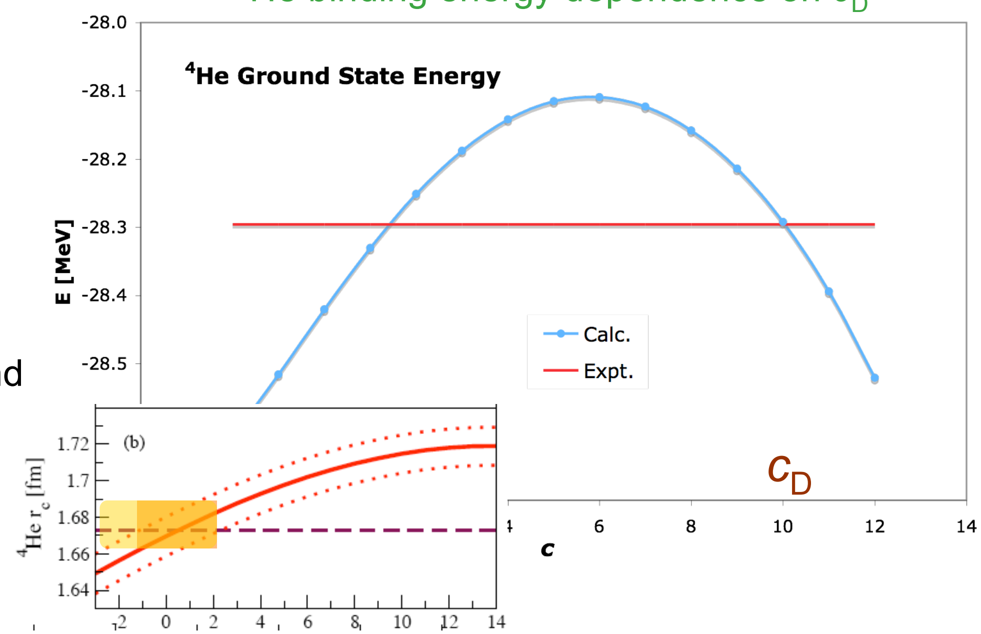
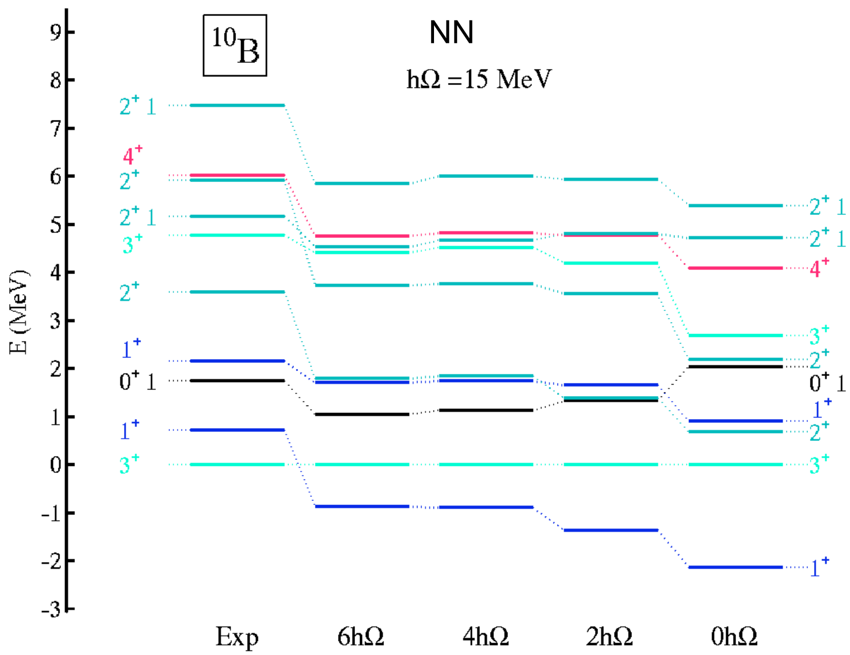
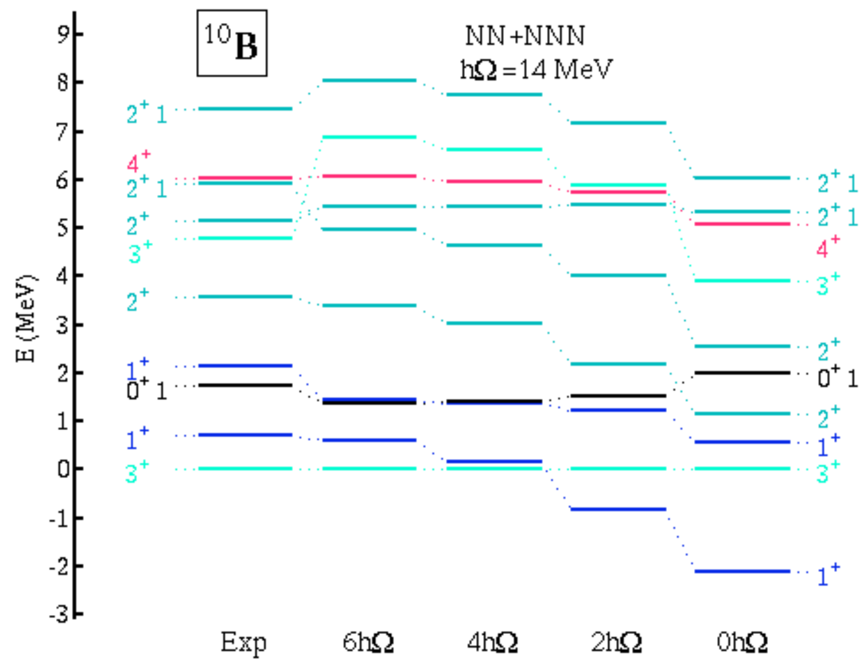


What about the structure of p-shell nuclei?

NNN is important for heavier *p*-shell nuclei: ^{10}B

- ^{10}B known to be poorly described by standard NN interaction
  - Predicted ground state 1^{+} 0
  - Experiment 3^{+} 0





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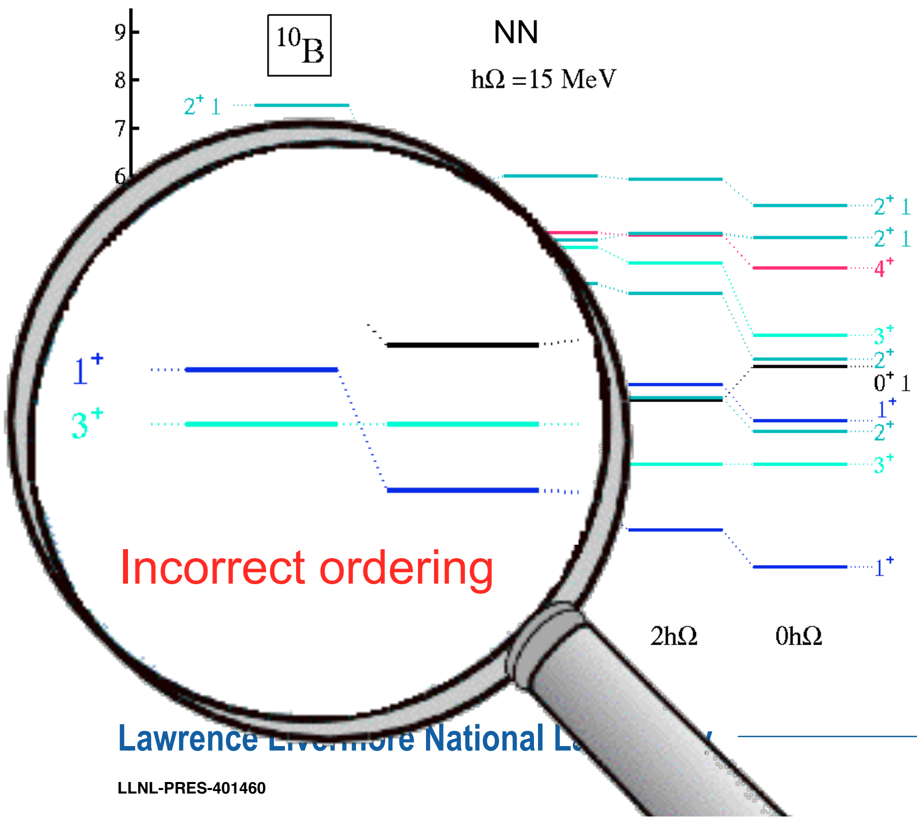

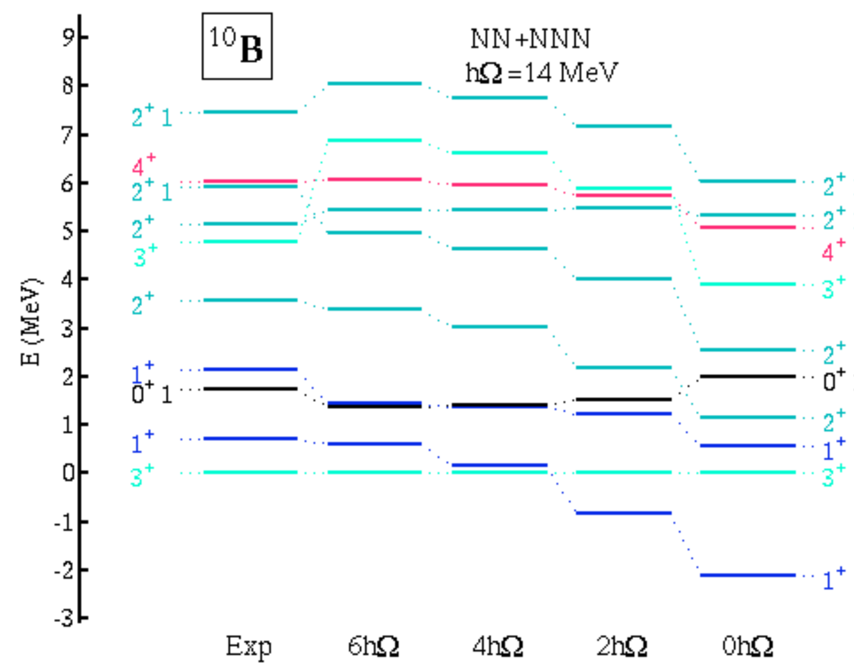

NNN important for heavier *p*-shell nuclei: ^{10}B

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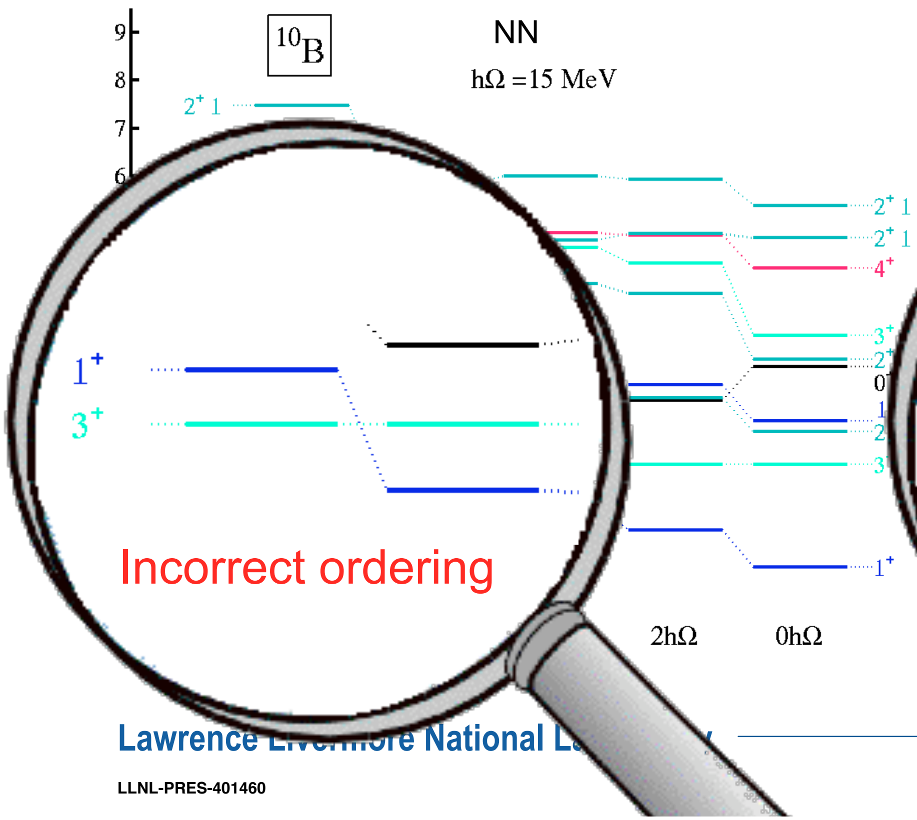
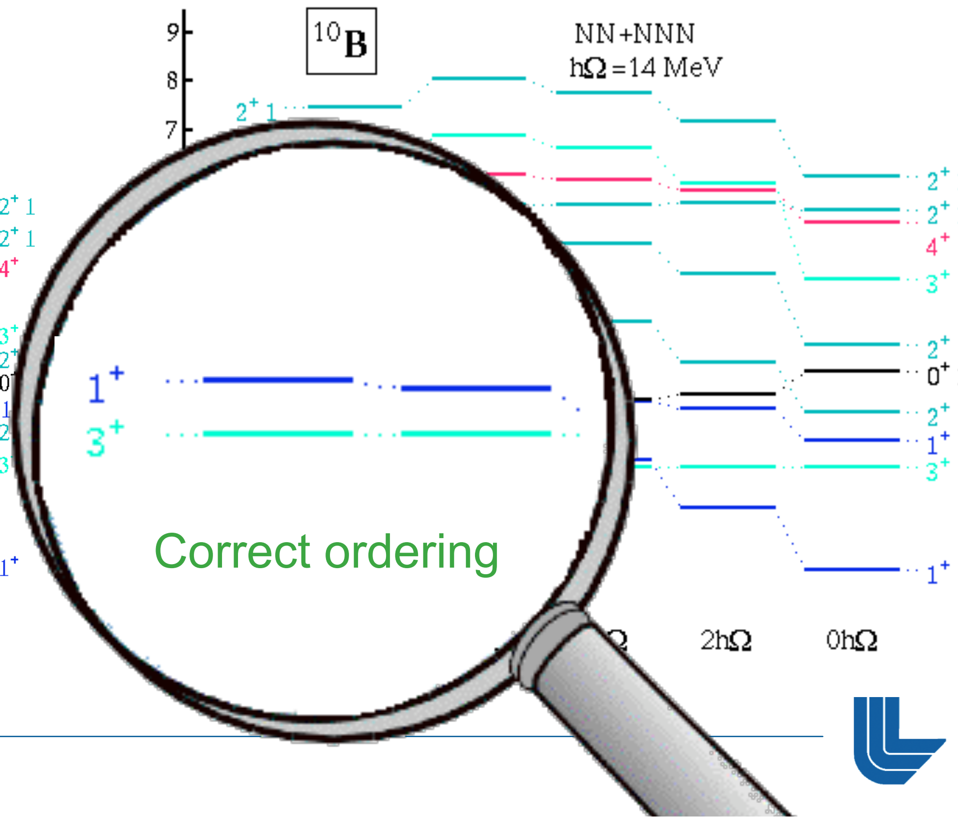
  - Experiment 3^+ 0
- Chiral NNN fixes this problem





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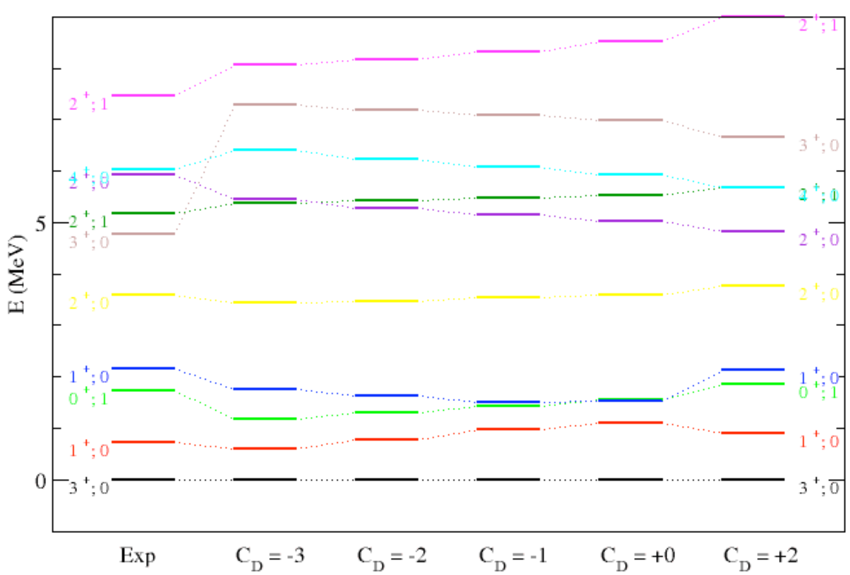
- Spectrum shows weak dependence on c_D

^{10}B NN+NNN c_D dependence for N_{max} = 6, hΩ =15 MeV



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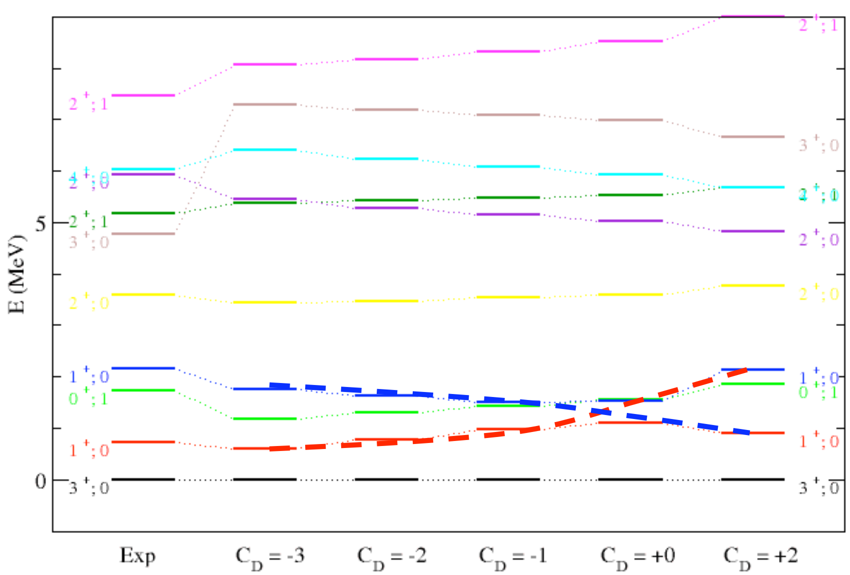

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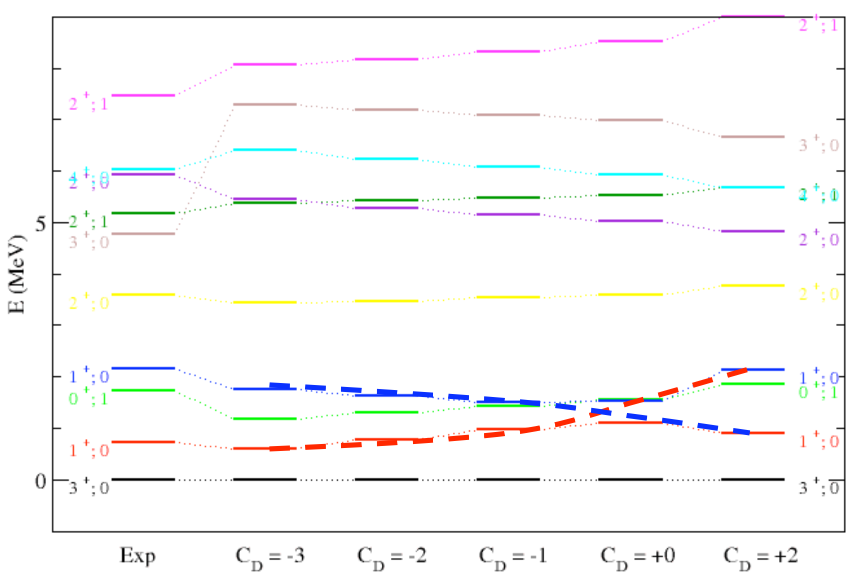

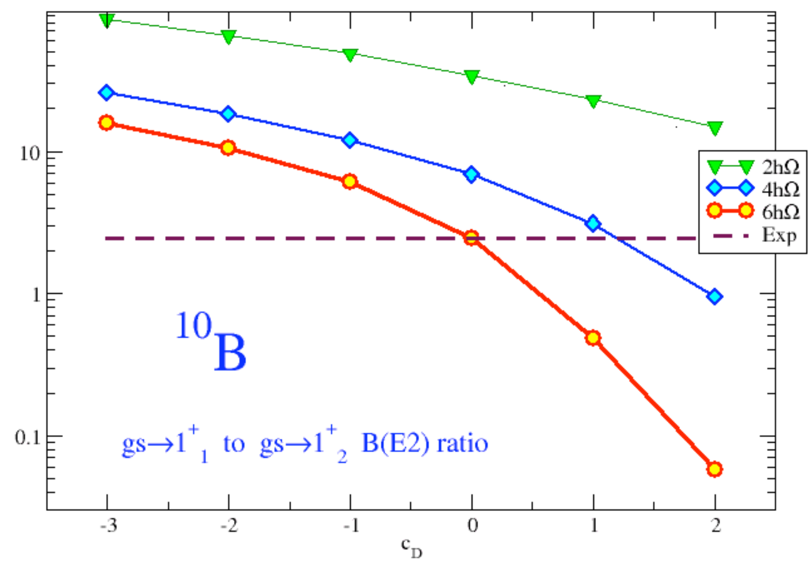

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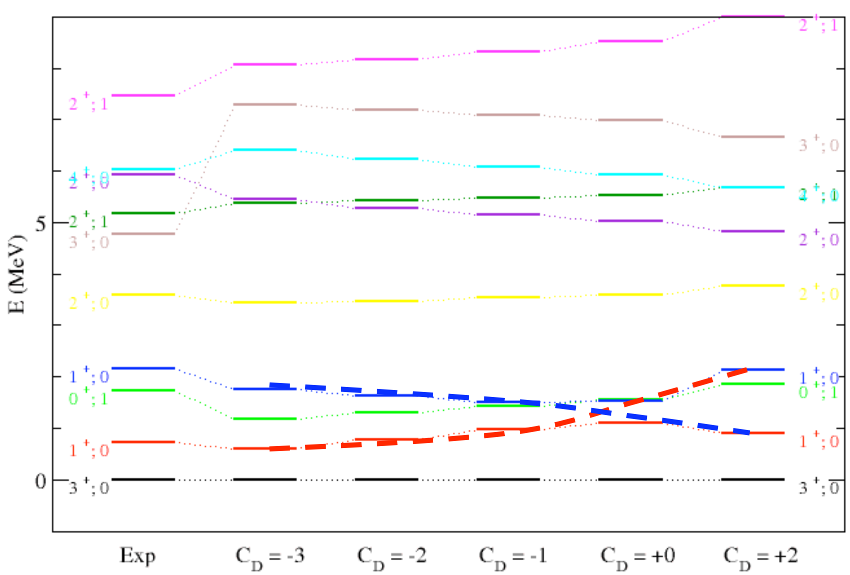
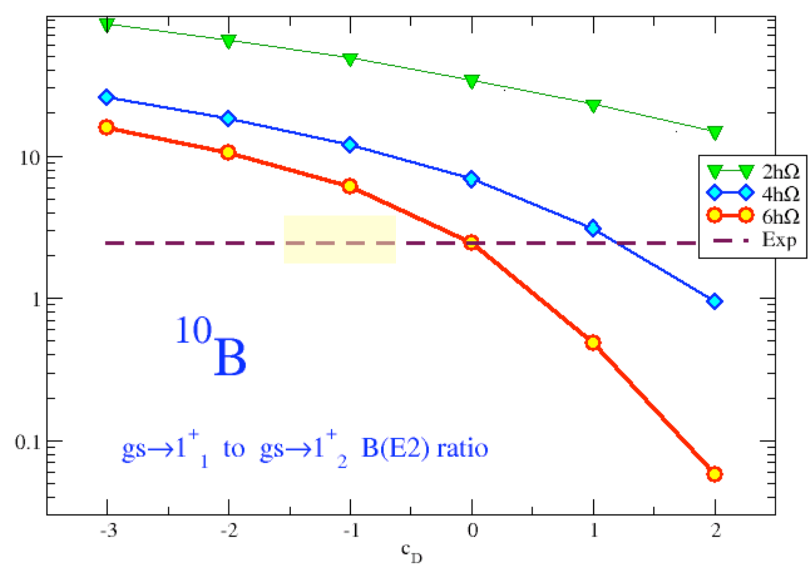
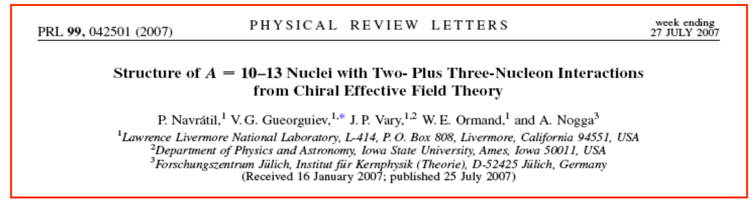




Structure of p-shell nuclei with NN+NNN interactions

- NCSM is only method capable to apply the EFT NN+NNN interactions
  - Technically challenging, large-scale computational problem
    - ~4000 processors used in ^{12,13}C calculations
- Applied to constrain the NNN interaction
  - Investigation of *A*=3, ^{4}He and *p*-shell nuclei
  - Globally the best results with c_D ~ -1
- NNN interaction essential to describe structure of light nuclei


PRL **99**, 042501 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

Structure of A = 10–13 Nuclei with Two- Plus Three-Nucleon Interactions from Chiral Effective Field Theory

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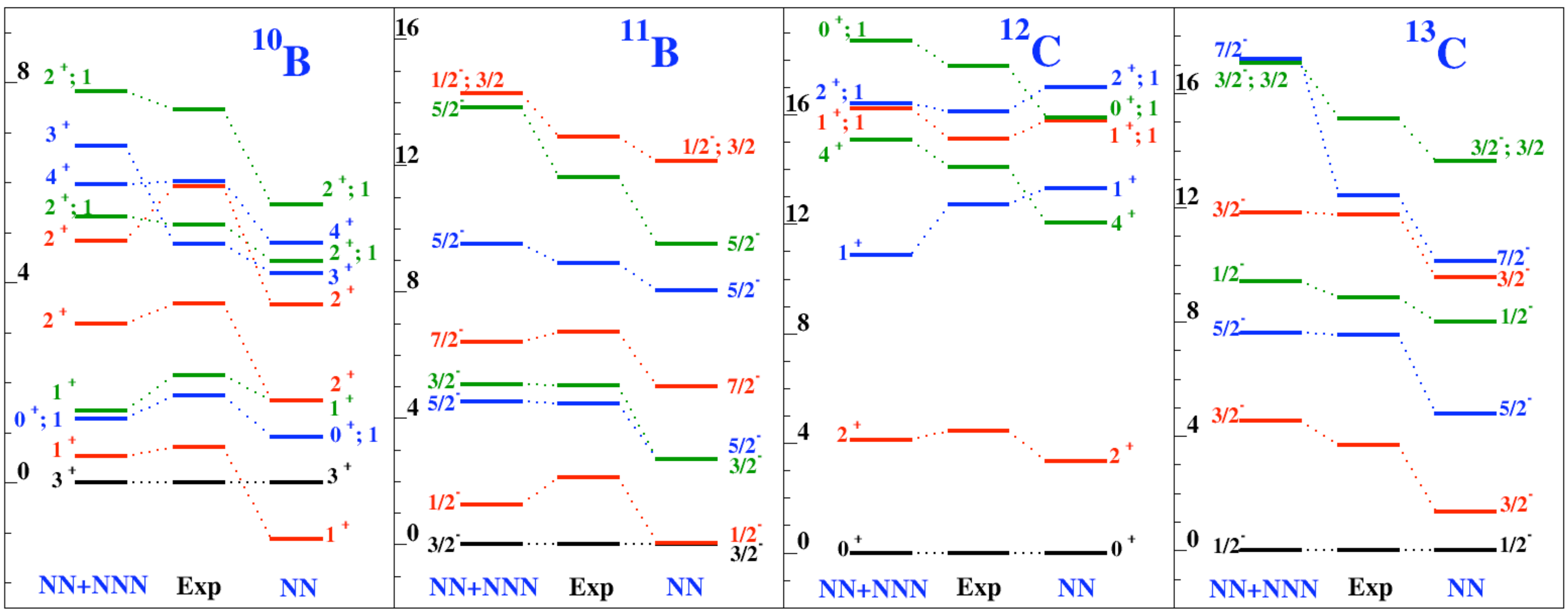
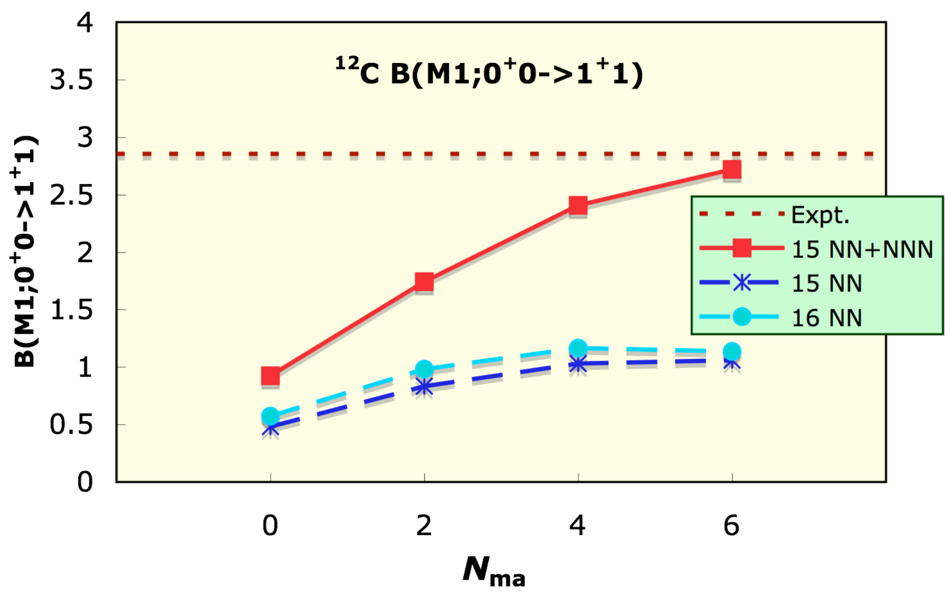


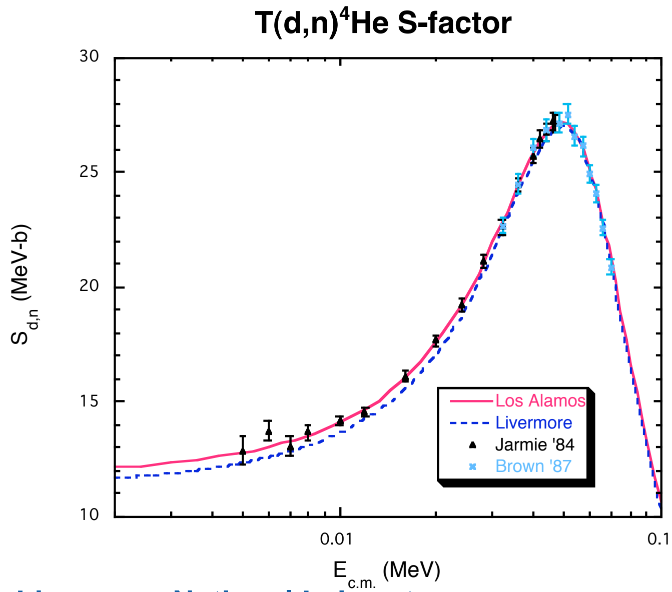
Spin-orbit physics and the NNN interaction

- Gamow-Teller and magnetic dipole transitions are sensitive to NNN
- Sensitivity of B(M1; $0^+0 \rightarrow 1^+1$) to the strength of spin-orbit interaction
  - Presence of the NNN interaction
  - Choice of the c_D-c_E LECs



From nuclei to stars:
ab initio approach to light-ion reactions

- *Ab initio* theory of nuclear reactions for $A>4$ basically non-existent
- Our goal is to provide accurate theoretical cross sections for reactions where measurements are very difficult or impossible
  - Light-ion fusion reactions at low energy:
    - T(d,n)^{4}He
  - Reactions of importance for astrophysics:
    - ^{3}He(α,γ)^{7}Be, ^{7}Be(p,γ)^{8}B, 2α(α,γ)^{12}C, ^{12}C(α,γ)^{16}O

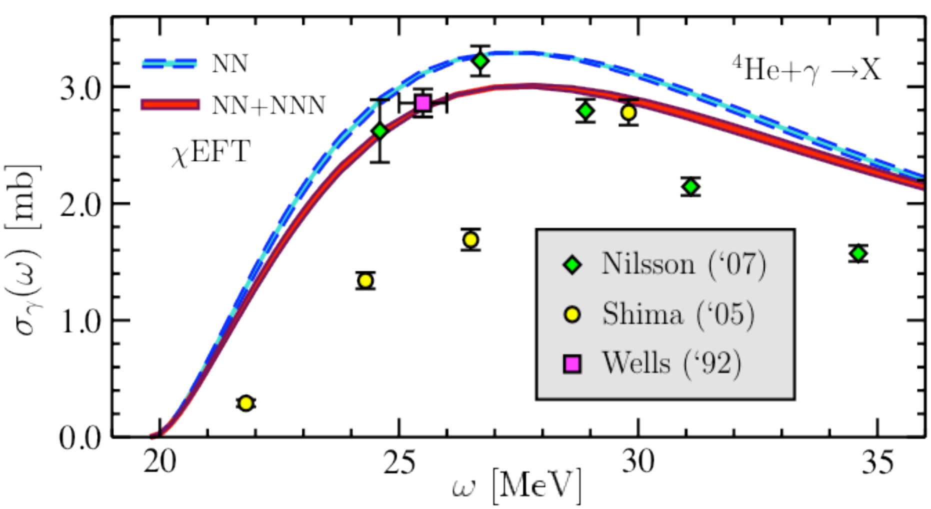


$$\sigma(E) = \frac{S(E)}{E}\exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2mE}}\right)$$

- low rates due to Coulomb repulsion
- low energies hard to reach in the lab
- large electron screening

Ab initio nuclear reactions: photodisintegration

- Photo-disintegration of ^{4}He
- Experiment is unclear
  - Can NN+NNN interactions give answers?
- The Lorentz-integral Transform method reduces the continuum problem to a bound-state-like problem



Appreciable effect of the chiral NNN interaction on the cross section
Data by Shima disputed

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The ^{4}He total photo-absorption cross section with two- plus three-nucleon interactions from chiral effective field theory

Sofia Quaglioni *, Petr Navrátil
Lawrence Livermore National Laboratory, L-414, P.O. Box 808, Livermore, CA 94551, USA

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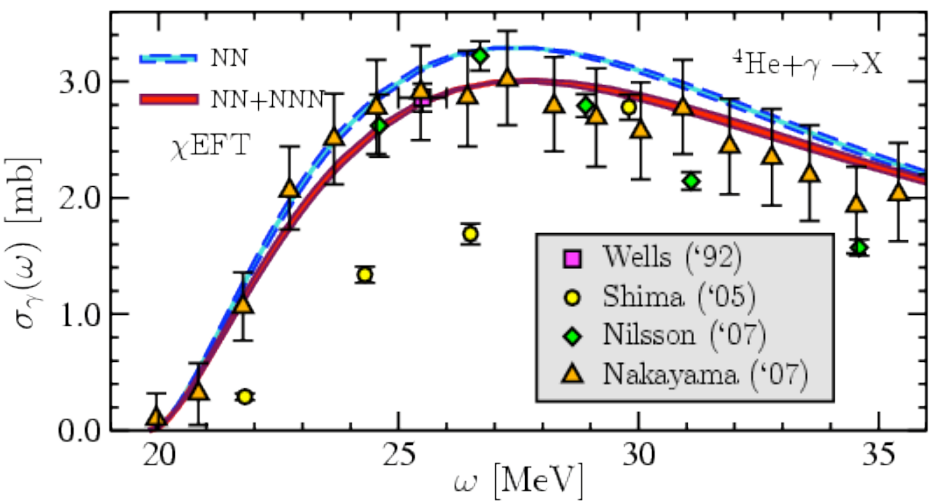

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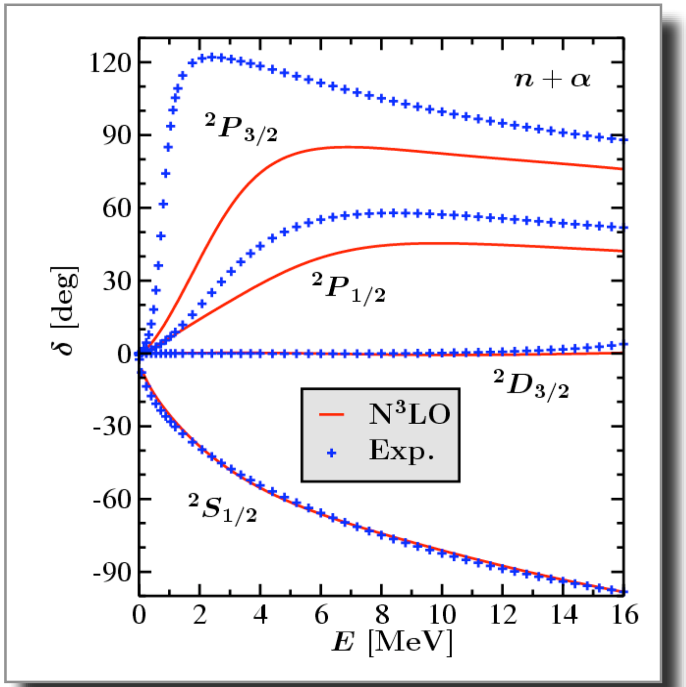
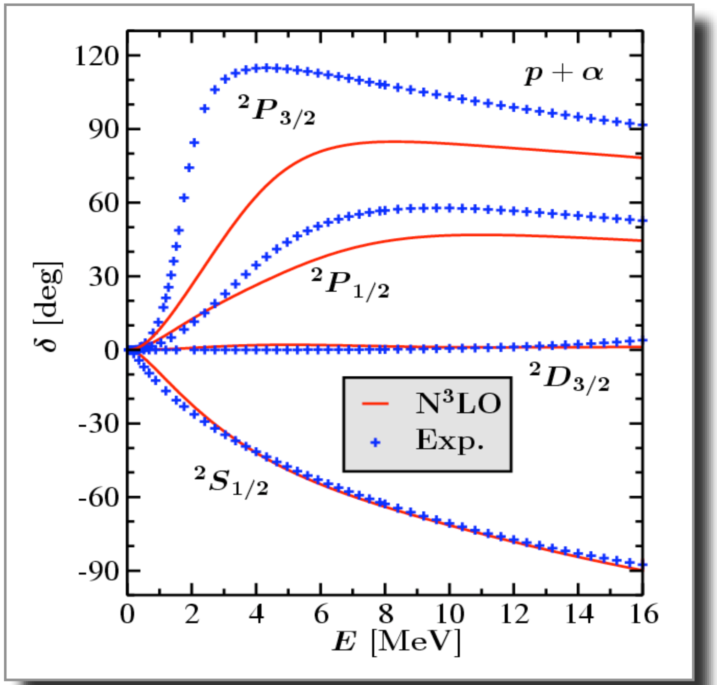
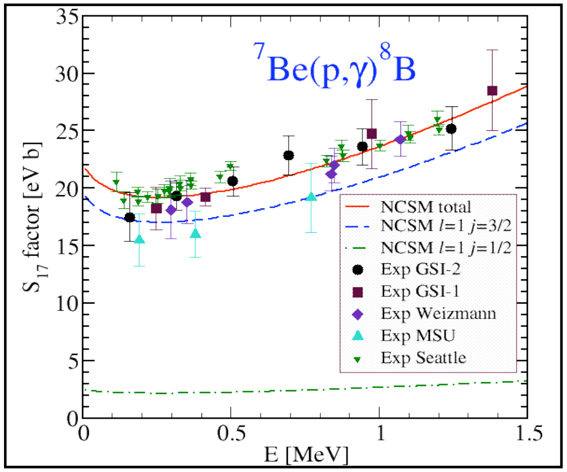
Ab initio reaction theory: nucleons

- We are developing a fully *ab initio* theory for nuclear reactions
  - Based on NCSM & Resonating Group Method (adds continuum)
- n+^{4}He & p+^{4}He scattering
  - EFT N^{3}LO NN potential
  - Agreement with experiment in the $^2S_{1/2}$ channel
  - Disagreement in P-waves due to missing NNN interaction terms





The future



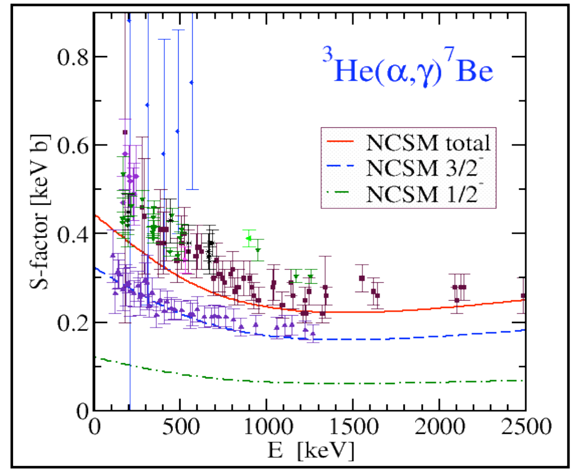
Highlight of DOE FY08 budget proposal to congress for nuclear physics

...

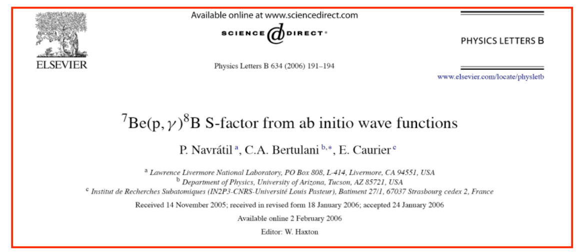
But not fully *ab initio*

....

Can we do better?



The next ATLAS Grand Challenge!



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^{7}Be(p,γ)^{8}B S-factor from ab initio wave functions

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- Augment the *ab initio* NCSM with the RGM technique
  - Includes clustering and resonant plus non-resonant continuum
- From QCD to Nuclei to Stars:
  - Develop a fundamental theory for low-energy nuclear reactions important for astrophysics
- We plan to compute ^{7}Be(p,γ)^{8}B and d(t,n)^{4}He this year

Summary

- High-profile science relevant to DOE/SC/NP mission
  - New insights on the properties of the NNN interaction
    - Responsible for “spin-orbit” physics in nuclei
  - New capability for nuclear reactions
    - Progress towards $^{12}C(\alpha,\gamma)^{16}O$
- Four LLNL publications
- Improved capability to compute cross sections for Lab programs
- Outside collaborations
  - J. Vary at ISU
  - Member of the UNEDF SciDAC-2 project